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## CHAPTER 9

## IN-FLIGHT ASSESSMENT OF WORKLOAD USING INSTRUMENT SCAN

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## INTRODUCTION

During instrument flight, the pilot obtains information concerning aircraft state by cross-checking or scanning the flight instruments. The exact method of scanning the instrument panel varies from pilot to pilot but there are some basic features common to a "good" scan pattern. Indeed, it was the early study by Fitts and his associates identifying the most common instrument transitions which led to the familiar "T" arrangement of the major flight instruments (1).

The method discussed here may be considered a candidate for workload studies with piloting tasks which will invoke a regular visual scan (spatial/temporal pattern of eye movements) during instrument flight. When instrument scan is in use, it may be postulated that external factors such as noise, interruptions, fatigue, etc which interfere with the piloting task may produce measurable changes in the scanning behavior. Such measures would be particularly attractive for quantifying workload since they would be both non-invasive and objective.

It is important to point out that instrument scan by itself is not a complete indicator of workload nor is task attention necessarily associated with where the pilot happens to be looking at a particular instant. However, whenever instrument scan is required in a piloting task, analysis of scanning behavior may yield important direct or indirect information concerning workload.

Scenarios in which instrument scan may be considered a potential candidate for workload assessment include:

- 1 Any situation in which instrument flight is required as part of the overall task,
- 2 Alterations in the design and/or layout of cockpit instruments,
- 3 Alterations in controls which require visual monitoring of.
- 4 Situations in which fatigue is suspected to be high.

## METHODOLOGY

## Measuring Visual Scan

Measurement of pilot lookpoint (eye point-of-regard) is required in order to analyze the instrument scan. While several techniques have been applied over the years, the most practical method for in-flight measurements is the remote oculometer. This device makes no contact with the pilot and does not restrict his movements while tracking his point of regard to within approximate 0.5 degree accuracy. The oculometer measures infrared light (from a low intensity source in a corner of the instrument panel) reflected from the retina and cornea of the eye via an infrared sensitive TV camera and a system of lenses and mirrors. Computer analysis of these reflections is performed to determine where the pilot is looking. Basic output from the oculometer consists of the x, y coordinates of the visual scene as a function of time. Temporal resolution is 1/30 second. For convenience in later analyses, the raw data is usually converted to yield instrument dwell rather than the x-y coordinates.

NASA Langley Research Center has devoted considerable effort to the problem of installing such a device in a cockpit. The current version of their electro-optical (EO) head requires a little more than the space of an instrument on the instrument panel. A more complete description of the oculometer is available elsewhere (2).

## Analyses of Scanning Behavior

Analyses of the information provided from the oculometer may be separated into temporal, spatial, and spatio-temporal categories. In all cases, the fundamental premise is that the 'regular' scan path will in some way be altered by some factor(s) (eg panel layout) which may affect workload during instrument flight. The analyses described here do not by themselves measure workload, however they allow comparisons of the scan path behavior of the pilot under various situations and thus may provide inferences concerning changes in workload.

## Temporal Analyses

## Time History of Lookpoint

The fundamental output from the oculometer is a time history of lookpoint (ie a plot of the instrument being viewed as a function of time). Besides providing the basic data from which other analyses may be performed this plot is useful as an overview of the scanning behavior; eg it is particularly easy to determine periods of 'staring' or high rates of blinking.

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### *Dwell Percentages*

The dwell percentage is the percentage of time spent looking at a particular instrument. The transition percentage is the percentage of transitions which occurred between two instruments regardless of the direction of the transition. These data are printed on a schematic view of the instrument panel with the dwell percentages inside the individual instrument boundary and lines between the instruments representing those transitions which occurred (the width of the line can be drawn proportional to the magnitude of the transition percentage). This diagram give a graphic picture of the scan paths.

### *Dwell Histograms*

Dwell time histograms may be plotted for each of the important instruments. Such a histogram is a plot of the number of dwells (looks) on an instrument which lasted for the length of time indicated by the abscissa. Intuition suggests that instruments with either high information content or poorer information transferability will elicit longer dwells than those with low amounts of information or good information transferability. When additional information is added to a display or the display format is changed, dwell histograms may be successfully used to examine the effect of this change on the pilot (2). The goal is to arrive at a display design which will provide the most information with the shortest dwell time.

Dwell time histograms tend to be stereotyped in shape for different instruments. Dwells can be classified by both the instrument being looked at as well as the function of the dwell, ie whether the pilot was monitoring information or changing the indication by some control input while looking at the instrument. The histograms for these two dwell functions have two peaks, one at short dwell times for 'check' on aircraft state and a second peak at longer dwell times associated with the 'reading' of aircraft state. The control dwells show a peak at a very long dwell time (2).

### *Oculomotor Dynamics*

Oculomotor dynamics are a useful type of ancillary data which may be considered during scan path analyses. While not a direct indication of scanning behavior, the details of how the eye moves between instruments may be an important indicator of fatigue. In particular, peak velocity and acceleration of saccadic eye movements can be expected to decrease dramatically as the oculomotor system fatigues. Measurement of these parameters can provide an indication of the tendency to fatigue under certain types of instrument scan.

### *Spatial Analyses*

#### *Instrument Transitions*

The earliest analyses of the instrument scan calculated the probabilities of a pilot making a change in lookpoint between pairs of flight instruments. The instrument transition matrix results from determining the probabilities of all such changes which are possible. While it is theoretically possible to statistically compare two such matrices, obtained under different workload conditions, the amount of data required to make such a comparison valid is often more than can be obtained in a practical situation. This fact led to the development of a single parameter measure of scan behavior, called entropy, which in effect summarizes the probabilities contained in the transition matrix (3).

#### *Entropy*

The time history of fixations has a form which is similar to that of a communication system which can assume  $N$  discrete states with a varying duration in each state. The orderliness of such a system is related to the probabilities with which it occupies its different states. A system which always occupied the same state or always made the same transitions between states would thus be quite orderly. In the case of instrument scan, these situations would be paralleled by staring and by a stereotyped scanpath respectively.

This concept of system order may be stated compactly (4) as:

$$H_o = - \sum_{i=1}^D [p_i \log_2 p_i]$$

where  $H_o$  = observed average entropy

$p_i$  = probability of sequence  $i$  occurring

$D$  = Number of different sequences in the scan

In the case of the instrument scan, entropy has the units of bits/sequence and provides a measure of the randomness (or orderliness) of the scanpath. The higher the entropy, the more disorder is present in the scan. The maximum possible entropy is constrained by the experimental conditions. The maximum possible value,  $H_{max}$ , may be calculated as follows. For a given number of instruments,  $M$ , and sequence length  $N$ , the maximum number of different fixation sequences is given by:

$$Q = M * (M-1)^{N-1} = \text{maximum of sequences of length } N$$

The number of bits required to uniquely encode all  $Q$  possible sequences is  $\log_2 Q$ . The magnitude of this latter number also represents  $H_{max}$  of the visual scan for the number of instruments and sequence length being considered. For example, with 7 instruments the value of  $Q$  for sequences of 2 instruments is 56 which yields a corresponding  $H_{max} = 5.8$ .

In order to include the effect of instrument dwell times, a term for entropy rate may be defined as:

$$H_{rate} = \sum_{i=1}^D [H_i / DT_i]$$

where  $H_i$  = entropy for  $i$ th sequence  
 $DT_i$  = Average dwell time for  $i$ th sequence  
 $D$  = Number of different fixation sequences

While it is possible for pilots to make rather rapid glances (with dwell times of 100 msec or less) at their instruments (5) a fixation rate this high (10 fixations/sec) rapidly leads to oculomotor fatigue. A more realistic average value is probably about 2 fixations/sec or less for a long period of instrument scan (say > 10 sec). Using this value (0.5 sec/look) as the average dwell interval, the maximum entropy rate for 7 instruments and sequences of length 2 is calculated from the following equation to be:

$$(H \text{ rate})_{\max} = 5.8/0.5 * 2 \text{ fixations/seq} = 6 \text{ bits/sec}$$

This number represents an upper bound. Since we suspect that the pilot must have some regularity in his or her scan, the numbers we would expect to obtain under actual flight conditions will probably be lower. The observed average rate for the basic experiments was on the order of 1 bit/sec. A tendency to stare under increased load should be reflected by decreased entropy and increased fixation times making  $H \text{ rate}$  tend toward lower values under such conditions.

### Spatio-temporal Analyses

#### Correlation

In situations in which a workload inducing stimulus is applied either periodically (eg verbal loading, secondary task, etc) or in a recurring but random fashion, the use of correlation methods may be in order.

Autocorrelation may be performed on scanning data as follows. A sequence of instrument numbers versus time is developed from the data. Due to the arbitrary nature of the assignment of instrument numbers, the autocorrelation of the signal containing all instrument numbers does not necessarily produce meaningful results. For this reason analysis of each instrument is examined successively by replacing the time sequence of all instruments with a sequence  $\{x(i)\}$  where the value is 1 for the instrument being studied and 0 for all other instruments. In order to eliminate the dc component for later spectral analysis, a zero-mean sequence  $\{f(i)\}$  is computed from  $\{x(i)\}$  as follows:

$$f(i) = x_i(i) - \bar{x}_j$$

where

$$x_j(i) = 1$$

if specified instrument  $j$  is being fixated and 0 otherwise

$$\bar{x}_j = \text{mean of } \{x_j(i)\}$$

The sample autocorrelation of  $\{f(i)\}$ , or sample autocovariance of  $\{x_j(i)\}$ , is calculated by the formula:

$$R_j(k) = 1/n \sum_{i=1}^n [f(i) * f(i+k)]$$

where  $R_j(k)$  = autocorrelation sequence for instrument  $j$

$n$  = number of samples = total run duration/oculometer sampling period (1/30th sec)

This autocorrelation is computed for each instrument for each loading case. In order to detect possible periodicity in the scan, the Fourier transform of the autocorrelation is taken to produce the power density spectrum. From this a value for the dominant frequency may be obtained. For skilled pilots, this frequency tends to be close to that of the workload stimulus which has been applied. This suggests that the pilot has a tendency to multiplex the flying task and the periodic task for greater efficiency. Overload occurs when numbers are presented too rapidly for the pilot to efficiently multiplex both tasks.

Novice pilots, however, do not seem to have any consistent pattern in their autocorrelation sequences. Most of these pilots show little or no periodicity in their scans for any of the loading conditions. One explanation may be that skilled pilots have a better developed ability to time multiplex several simultaneous tasks.

For stimuli which occur repetitively, but not at periodic intervals, it is plausible to consider the use of cross correlation between the time at which the stimuli are applied and the scanpath although this has not been attempted to date.

### Visual Scanning Measures Applied to the Standard Flight Task, (Manually Flown ILS Approach and Landing of Two-Pilot Passenger Jet Transport).

We now briefly discuss the application of our techniques to the valuation of workload during an ILS approach. Two or three factors must be manipulated to use the techniques described above: (a) a piloting task requiring a stereotyped scan path, (b) a verbally presented mental loading task, or (c) a visually presented mental loading task. It is assumed that the cockpit to be used for the experiments may be outfitted with the NASA Langley oculometer system or an equivalent and that ample time will be allowed (approximately 5-10 minutes) for calibration of the oculometer before an experimental session begins.

The proposed ILS approach scenario requires the use of a stereotyped scanpath, though it should be emphasized that the task and hence the scan pattern is not constant throughout the scenario. Thus, the second to second level of loading due to the flight task and the corresponding instrument scan will vary, albeit in a somewhat predictable fashion. The additional verbal or visual loading task serves to "bias" the total amount of mental load on the pilot with the goal of locating peaks in the load due to the piloting task alone. The notion here is that the workload due to the additional task is roughly additive with the instantaneous load due to the piloting task. The hope would be to bias the total load to a high enough level to demonstrate a performance decrement (which may be a non-linear function of loading) while at the same time hopefully observing a monotonic change in the measures of scanning behavior as a function of the increased load.

Several levels of difficulty of the additional task are required. These may be achieved in two ways. A constant level of difficulty may be imposed over the entire approach; this method is to be recommended at present as we are not as yet sure how to analyse short segments of the scan pattern. Each level of difficulty of the imposed extra task would thus require a separate run. Since both the verbal and visual tasks are periodic, their respective difficulties may be altered during a run by changing the period between presentations of the task. This method would seem more attractive if the piloting task were indeed fixed over the entire run.

A verbal task may be used as one means of biasing the loading level. This has been shown to work well in our experiments and is easy to implement and score (6). Such a task should be designed to approximate one which would ordinarily be performed in the course of flight; eg a constant rate of radio communication or periodic manual computation of navigational coordinates.

An alternate, visual version of this task is also possible and perhaps more appropriate for actual flight conditions. A small display could be mounted in a convenient point in the pilot's visual field. The display could present either a "+" or a "-" sign. At periodic intervals an auditory "beep" would signal that the pilot should observe this display and indicate (operationally) via a rocker switch whether the display is currently indicating + or -. The interval between "beep" determines the difficulty of this task and one possible measure of workload is the % of time the pilot is actually able to observe the display.

Entropy rate calculations could be made on the scanning data regardless of whether the visual or verbal loading task is used. Since both tasks are periodic, the autocorrelation technique may also be applied. Although we have not done it as yet, we expect that cross correlating the time of presentation of the imposed task with the scanning data is likely to yield good results especially in the type of flight scenario proposed in this study. We expect that a characteristic "signature" will appear in the cross correlation between the loading task and the instrument scan and that this signature will be altered via changes in task difficulty.

#### Limitations and Pitfalls of the Technique

There are a number of potential problems in applying our techniques. These are enumerated below:

- 1 The piloting task being performed must require instrument scan.
- 2 The relationship between where the pilot is looking and the 'focus' of his attention may be misleading (clearly this is the case if the pilot is staring).
- 3 The scan must be repetitive, at present, although it may be possible (eg using cross correlation) to analyze short segments of a scan pattern.
- 4 An onboard oculometer is required and must be mounted in the instrument panel (NASA — Langley Research Center has worked out many of the technical problems however). Jet Transport simulators at NASA Langley and elsewhere have also been fitted with the oculometer.
- 5 It may be necessary to calibrate without the pilot's cooperation due to time limitations in the proposed experiments. However sufficient setup time prior to the experiment will minimize the calibration needed.
- 6 The behavior of the various measures of scan has not been examined under a wide variety of situations as yet, hence we are unable to comment on flight scenarios in which the task is most applicable other than the obvious requirement of some type of scanning behavior.

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